PRODUCING NIF'S OPTICS

J. Atherton
D. Aikens
J. Campbell
J. De Yoreo
R. Montesanti
T. Parham
C. Stolz

The NIF will be the world's largest optical instrument. The basic challenge for producing optics for NIF is to establish and maintain high production rates and low costs while meeting tight technical specifications. We are working with industry to develop advanced manufacturing technologies that will help meet this challenge. Our optics development program has been very successful to date: most production process details are finalized, and key results have been demonstrated in many areas. We are on schedule and, as of Title I, are soliciting competitive proposals in most areas, consistent with the overall NIF schedule.

Introduction

Within the NIF optical system, we have more than 7000 large optics that handle the full-sized NIF beam (0.5 to 1 m maximum optical dimension), and about 15,000 to 20,000 smaller optical components. The technical requirements for these optics present many challenges for their production. For instance, most damage thresholds are about three times higher than Nova's, and at or above Beamlet's levels. Other challenges are in the areas of schedule and cost. First, we have an extremely short production schedule. Installation of the optics must begin in FY99 and be completed by the end of FY02. This means that procurement bids must be awarded by mid-FY97 for the start of final facilitization for optics; pilot production must start in late FY98; and production must begin by FY99. The fact that we need thousands of meter-class optics also puts pressure on the schedule. At present, the U.S. optics industry can produce about 200 to 300 meter-class optics per year—about 10 times too low for our needs. As for costs, the extreme technical requirements and tight time restraints work against efforts to keep costs low.

We are working with the U.S. optics industry, as well as with University of Rochester's Laboratory for Laser Energetics (LLE) and Los Alamos National Laboratory (LANL), to develop the technologies needed to meet NIF's goals and requirements within time and budget. Our partnership with industry is nothing new. We have worked with the optics industry since LLNL began researching inertial confinement fusion with large laser systems, beginning with the Janus laser system in 1974. We have helped advance the state-of-the-art in optics manufacturing technology to increase production volume and performance, and to decrease production costs for optics of NIF size.

We and our partners are following a four-part program—development, facilitization, pilot production, and production—to meet NIF's optics performance, schedule, and cost requirements. Figure 1 shows the production areas and the schedule for each.

To date, most of our activities in these areas have been in the development program. This program's goal is to reduce optics cost and improve performance of NIF's significant optical components (Table 1). Our development program has yielded some impressive results to date, particularly in the areas of continuous melting of laser glass, potassium dihydrogen phosphate crystal (KDP) rapid growth, KDP diamond turning, deterministic high-convergence figuring, and coating designs for polarizers. We still have concerns in some areas, but in general, our strategy is to use multiple vendors and backup technologies to minimize risks to production costs and schedules.

As for Title II activities, we are proceeding in a manner consistent with the overall NIF schedule. We are now soliciting competitive proposals in most areas, and final facilitization for optics is scheduled to begin in mid-FY97.

The rest of this section summarizes our activities and future directions for each of the areas listed in Figure 1.

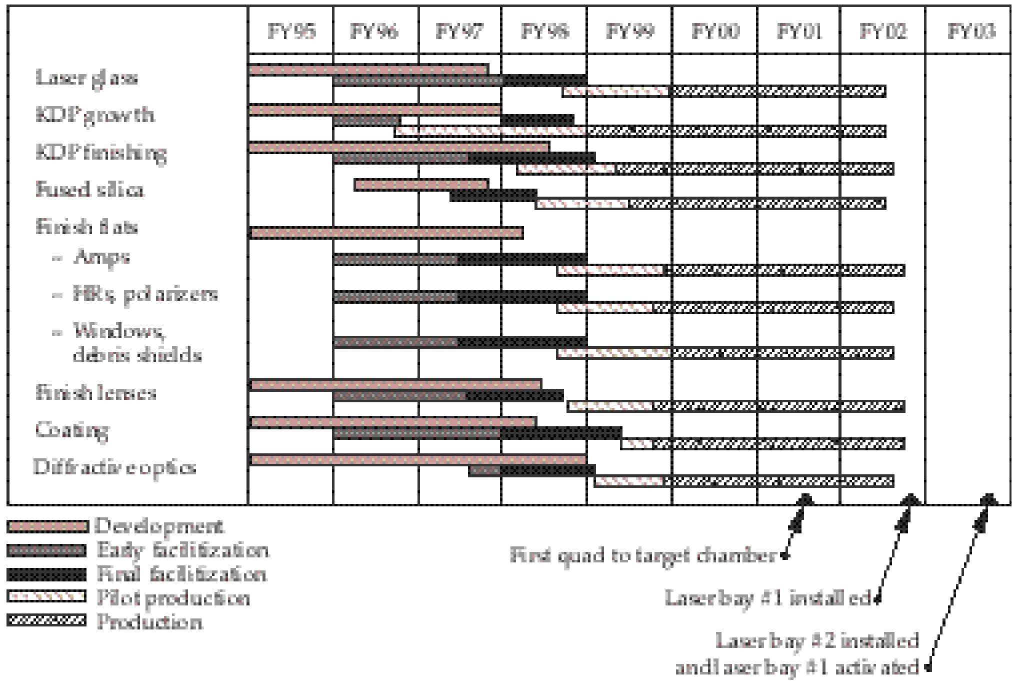


FIGURE 1. Schedule and areas of focus for NIF's optics development, facilitization, pilot production, and production programs. (40-00-0997-2072pb01)

TABLE 1. The development program is focusing on the technologies that will improve performance and bring costs down for amplifier slabs, crystal optics (i.e., frequency converters and Pockels cells), polarizers, and lenses.

Optical component	Beamlet actual	NIF production estimate (FY96$)	Development required
Amplifer slabs	$49K	$17.5K	Continuous melting / forming of laser glass High-speed grinding / polishing Deterministic figuring
KDP / KD*P crystals	$34.3K–$73.5K	$15.7K–$25.3K	Rapid growth of KDP / KD*P Low-modulation diamond turning
Polarizers	$43.2K	$19.2K	Improved yields in coatings Reduced defects; increased damage threshold from >12 J / cm^2 to 20 J / cm^2 at 1053 nm
Lenses	$28.5K	$12.3K–$14.1K	Reduced inclusions, NIFboule geometry in fused silica Deterministic figuring of square lenses Maintain large-area damage threshold >14 J / cm^2 at 351 nm

Estimates based on vendor cost studies

Laser Glass

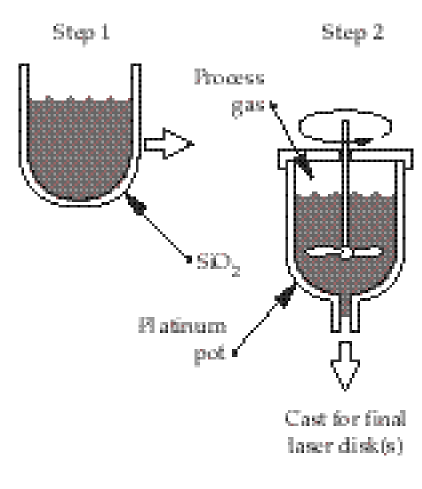
The laser glass effort involves producing the "blanks" of neodymium-doped glass that are later machined into amplifier slabs. The NIF Title I design requires well over 3000 laser glass slabs—11 in the main amplifier and 5 in the power amplifier for each of the 192 beamlines. These neodymium-doped slabs must have certain characteristics for fusion laser applications: they must extract energy efficiently from the flashlamps that pump them, store that energy efficiently and at a high density, and be of high optical quality (i.e., high homogeneity, low nonlinear index, low thermal distortion, high damage threshold, and low losses).

At 80 × 46 × 4 cm, NIF's slabs are slightly larger than Beamlet's slabs, which are roughly twice the size of anything previously produced. To produce laser glass in the size and volume required by NIF, our vendors are developing a "continuous melting" technique to replace the more common "batch melting" technique (see "Melting Methods for Glass" below). There are only two laser glass vendors in the U.S. capable of producing the NIF slabs: Schott Glass Technologies, Inc., and Hoya Corporation / Hoya USA. They are taking different approaches to solving the technical issues involved with the continuous melting technique. Hoya has designed, built, and operated a subscale continuous melter to study key development issues, whereas Schott has decided to design and build a full-scale continuous melter starting in early 1997, with operation starting in late 1997.

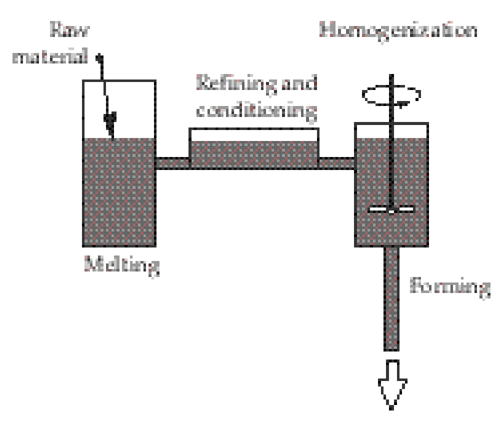
MELTING METHODS FOR GLASS

There are two possible methods for producing the glass needed for NIF's amplifiers: the discontinuous or "batch" method and the recently developed continuous method. In the more common batch process, as shown here, raw materials are first melted and stirred in a quartz vessel. The melt is cooked, broken up, and the fragments or "cullet" are melted, refined, and stirred in a platinum vessel. The contents of the vessel are then poured onto a moving conveyor to form the glass blanks. The batch process has serious drawbacks when applied to NIF. The vessel must have a volume of approximately 50 L to produce a single blank with a volume of about 10 L; hence most of the glass is wasted. In addition, the batch-to-batch variations are greater with a batch melter than with a continuous melter, thereby reducing yield and increasing cost.

In a continuous melting furnace, the raw materials melt and mix in one chamber, then flow as a liquid into refining and homogenizing chambers. A continuous liquid stream of glass runs out of an aperture in the homogenizing chamber. This process, shown here, is much better suited to manufacturing the large volumes of glass that NIF requires.



Batch melting process for laser glass
(40-00-0496-0936pb02)



Generic continuous melting process for optical glass
(T. Izumitani, *Optical Glass*, 1985, Chap. 3)
(40-00-0997-2077pb01)

KDP Growth

NIF requires 600 large-aperture KDP components for optical switches and frequency converters for its 192 beamlines. For NIF, there are three main issues driving KDP development. First is performance, including the threshold for 3ω damage in KD*P, KDP and KD*P wavefront requirements, and surface modulations. Second is risk: using conventional crystal growing methods, it takes longer than two years to grow KD*P crystals of the size needed for NIF. In addition, the yields from the conventional growing process are highly uncertain. Third, we have cost considerations. The average cost of KDP plates for Beamlet was $65K / plate; we hope to bring this cost down considerably. Also driving KDP development efforts are the NIF requirements for the crystals, including sizes, surface finish, and the fact that we need 600 crystals within three years.

We are taking two approaches to meeting these challenges. At LLNL, we have designed, built, and tested a full-scale rapid growth system, while Cleveland Crystals, Inc. (CCI) is improving conventional crystal growing technology as a backup technology for NIF (see "Growing Crystals" below).

We have demonstrated that, with rapid growth, we can meet all NIF crystal requirements at the 15-cm scale and almost all in 41-cm z-plates. For both technologies, we still need to demonstrate full-aperture growth for the doublers and triplers used for frequency conversion. We have two issues to address for large-scale rapid growth: inclusions, which can cause damage, and spontaneous crystallization under certain conditions.

Our Title I strategy for delivering NIF crystals has two parts: one for our rapid growth technology, the second for our CCI backup technology. For rapid growth, we plan to demonstrate the technology at full-scale by mid-FY97, and provide limited optimization in mid- to late-FY97. We will transfer the technology to vendors for NIF production in FY98 and also conduct some pilot production at LLNL as a backup. CCI will begin upgrading their facilities in mid-1997, allowing six years for a NIF pilot plus full production. If CCI uses crystal seeds from our rapid growth efforts, this time could be less. Major issues for this strategy include LLNL being ready to transfer the technology to vendors by early FY98 and determining how many vendors to include in the facilitization, since those costs are high. Finally, the timing for CCI facilitization and seed production is still evolving.

KDP/KD*P Finishing

To get from a crystal boule to a finished piece requires precision machining and finishing. There are two general steps to the finishing process—blank fabrication and final finishing. In blank fabrication, the blanks are sawed from a boule before being processed to a final size and flatness by single-point machining. In final finishing, the final surfaces of the crystals are generated by single-point diamond flycutting. The two major challenges for crystal finishing are the tight specifications and the high production rate.

Three crystal finishing specifications for NIF are particularly difficult to meet: surface roughness, surface waviness, and reflected wavefront. We are making progress in all three areas. Improvements to the diamond flycutting machine at CCI reduced the surface roughness and waviness of crystals by a factor of three. CCI has now met NIF reflected wavefront requirements on a 37-cm Beamlet crystal.

GROWING CRYSTALS

In general, crystals are grown from a seed or "starter" crystal, which is submerged in a melt or solution containing the same material. The final growth, which has the same atomic structure as the seed, is called the boule. Conventional techniques for growing crystals from solution are generally slow; growth rates for conventionally grown KDP are about 1 mm / day. Because of a high density of defects in the material near the seed crystal in KDP, the quality in this region of the crystal is low; and because the seed defects propagate into the final boule, a substantial fraction of the boule is of low quality. A large percentage of crystals that have taken a long time to grow are, in the end, useless for their intended purpose.

LLNL's rapid growth method, which derives from research at Moscow University, uses a small "point" seed and produces only a small number of defects. As a result, even material near the seed is of high quality. The process relies on pretreatment of solutions using high temperature and ultrafiltration. This process destroys any small crystal nuclei that might be present in the solution and allows it to be highly supersaturated without spontaneous crystallization. Of secondary importance to this method are the technique for holding the seed, the temperature profile during growth, and the hydrodynamic regime. The two major advantages of this process—high growth rate and potentially high yields—dramatically reduce cost.

An aggressive production schedule means that finished pieces must be completed at three to four times the current production rate. CCI plans to purchase new equipment and streamline their process to meet NIF's schedule, perhaps running two or three shifts instead of the current 1.5.

The major challenges for production are achieving flatness and diamond flycutting the faces. The current method for achieving crystal flatness was developed for Nova. CCI has developed a proprietary process that produces flatter surfaces. Additional process development is aimed at making the new process more deterministic and faster. The diamond flycutting machine can finish a crystal to NIF specifications, but takes about a week to do it. To meet the production rate of one crystal / day will require a new, state-of-the-art machine. The Laboratory and France's Commissariat a l'Energie Atomique (CEA), which also requires KDP components for its Laser Megajoule (LMJ), have commissioned to build two such machines.

Our outstanding tasks for the future include refining the process for efficient part flow and designing and building equipment for blank fabrication. For final finishing, we need to optimize the process to reduce fogging on the flycutting machine and to design the new machine. Finally, for facilitization, we need to select the finishing vendor and install and check out equipment.

Substrates for Mirrors, Polarizers, Lenses, and Windows

The eight NIF mirrors and polarizers in each beamline, highlighted black in Figure 2, will be made of a readily available optical glass (BK7™ or a similar equivalent). Ten large aperture lenses and windows, shown gray in Figure 2, will be made of fused silica. Our focus in the area of substrates is on the cost and schedule for the fused silica components rather than the technical requirements.

We are working with Corning Inc. to improve its synthetic fused silica deposition process to increase the yield. First, the boule geometry will be better matched to the NIF blank size to maximize the number of blanks obtained from each boule. Second, the process design and control will be improved to reduce inclusions. Finally, the boules will be more efficiently processed to reduce metrology needed for quality assurance.

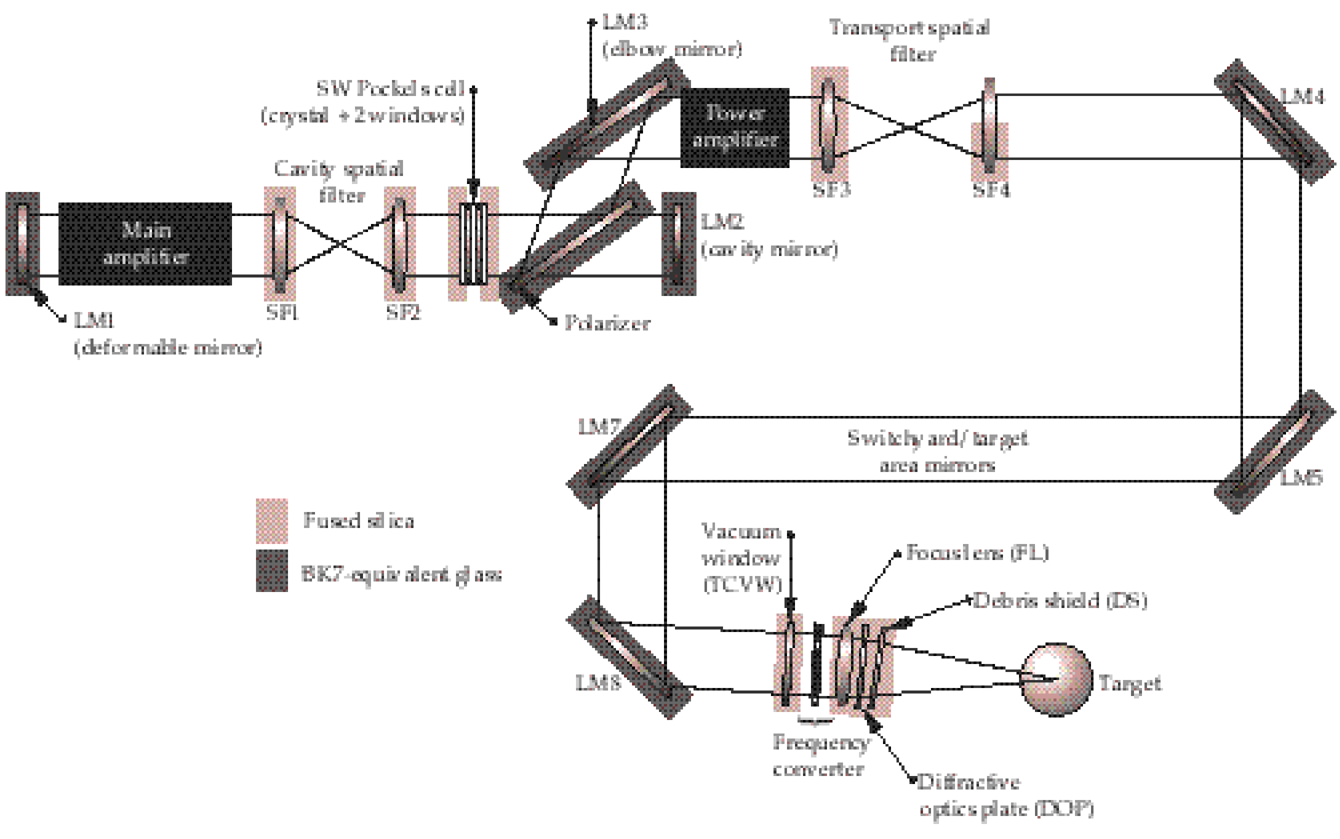


FIGURE 2. Eighteen large-aperture optical components in each NIF beamline, about 3500 total, will be fabricated from glass substrates. The components in black will be based on a BK7™-equivalent glass; the components shown in gray will use fused silica. (40-00-0997-2073pb01)

In addition to these yield improvement activities, we are also investigating the homogeneity specification of the fused silica blanks. Improved figuring capability at the optics fabrication vendors may allow us to significantly relax the homogeneity requirements of the glass for some of the optics. In this manner, the glass yield can be increased and the cost decreased, without significantly impacting the overall cost of the fused silica optics or the performance of the optics in NIF.

Optics Fabrication for Flats and Lenses

The optics fabrication process takes optics materials—laser glass, fused silica, BK7™—from the raw blanks to polished surfaces. The blanks are shaped with machine tools, similar to those used in metal fabrication. This machining process leaves a significant amount of subsurface damage, which is removed through lapping and polishing. The most expensive, time-consuming fabrication step is iterating to achieve the final figure. To achieve NIF cost targets, this final figuring step needs to be as automated and deterministic as possible.

Most of the functional performance requirements, such as achieving the proper shape and meeting wavefront requirements, have been demonstrated. We have three primary concerns still to address. First, finishing vendors must consistently meet NIF smoothness and ripple requirements. Second, they must establish the capacity necessary to meet NIF's schedule (i.e., completing 30 lenses / month, 90 laser slabs / month, and 80 mirrors and windows / month). Finally, they must demonstrate and consistently achieve high 3ω damage thresholds of 14.1 J / cm^2 (for the focus lens, diffractive optics plate, and debris shield only). To meet the performance requirements and cost targets at the needed throughput will require a highly optimized process, and new and custom machine tools.

In FY97, lens development efforts will focus on meeting specifications as well as throughput and 3ω damage requirements. In flats fabrication, we will be funding development at three companies to broaden the competitive field. All throughput and performance requirements for flats fabrication will be demonstrated at full scale during FY97 and FY98.

Optical Coatings for Polarizers and Mirrors

Each of the large-aperture mirrors and polarizers in the NIF beamline has its own, often very complex, coating requirements. Meeting the fluence requirement for the transport mirrors represents the greatest technical challenge for coatings. As for meeting cost and schedule constraints, our greatest concerns involve the yields and capacity. For instance, poor yields translate to high costs per unit. In addition, NIF is not the only project with optical coating requirements. Competition from other LLNL and Department of Energy programs potentially restricts NIF's access to coating chambers, which could impact the schedule.

Looking at the coating process used on Beamlet, we find that many of the NIF coating technological requirements have already been demonstrated with Beamlet optics. This coating process can be improved without major process modifications, which will increase the yields. This leaves the issue of capacity. Since coating is the last step in the optical manufacturing process, we need extra capacity to compensate for any schedule slips in earlier steps. Vendors are working on ways to increase their capacity and meet NIF's requirement of coating about 10 optics / week. We are also working with other programs that have optical coating needs, to see if their needs can be met with the smaller coating chambers, freeing up the larger ones for NIF. We will minimize the number of test runs and subsequent coating costs by grouping the optics into "campaigns." Finally, we are working with vendors to optimize the metrology to increase the throughput.

Diffractive Optics

We have diffractive structures on two components in NIF's final optics assembly. The final focus lens has a 3ω sampling grating on the flat, incoming surface, and the diffractive optics plate has a color separation grating (CSG) on the incoming surface and a kinoform phase plate (KPP) on the outgoing surface. These diffractive optics are fabricated at LLNL in our diffractive optics lab. We have produced 3ω sampling gratings that meet NIF's requirements. We have also fabricated KPPs for Beamlet and Nova that meet the NIF energy requirement of 1.8 MJ, but we need to improve the beam divergence. Finally, we have produced a subscale CSG part that meets the minimum performance specifications.

We can meet the Title I performance requirements for diffractive optics with the existing process technology, which is based on interference lithography for the 3ω sampling gratings, and conventional photo-lithographic techniques for KPPs and CSGs (see Figure 3). However, to meet our cost and yield projections, we must complete several activities. First, we must decide by mid-1998 between two techniques for etching patterns into the KPP fused silica substrates: the existing wet etch technique or a reactive ion etching (RIE) technique under development. The RIE involves fewer manufacturing steps, and would improve KPP performance and reduce costs. For the CSG, we must improve the precision of the mask alignment from 2 μm to 1 μm to minimize errors at the shorter ~240-μm period. Finally, we need to upgrade our facilities. We have already begun modifying the facility to provide processing for the 3ω sampling gratings and CSGs. We will add RIE capabilities, if our development effort shows that it would be cost effective to do so.

For more information, contact
L. Jeffrey Atherton
Associate Project Leader for Optics Technology
Phone: (925) 423-1078
E-mail: atherton1@llnl.gov
Fax: (925) 422-1210

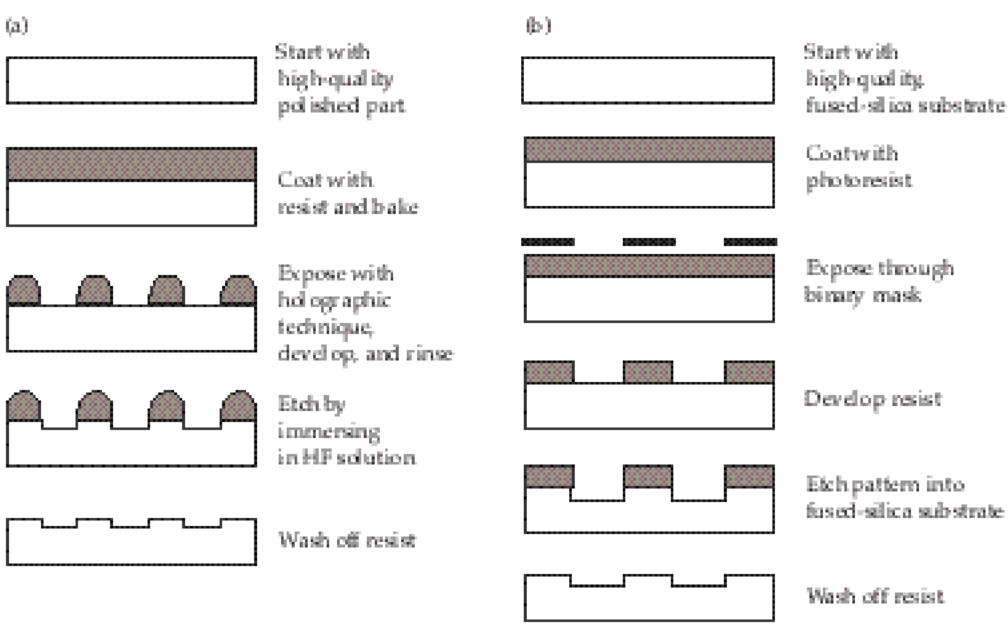


FIGURE 3. The NIF baseline process for producing 3ω sampling gratings and kinoform phase plates (KPPs) and color separation gratings (CSGs) are based on lithographic techniques. (a) The sampling grating uses interference lithography with hydrogen fluoride wet etching. (b) The large-scale features of the KPP and CSG allow us to use conventional photolithographic techniques. (40-00-0997-2075pb01)